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Institutional impediments to conservation of freshwater dependent ecosystems

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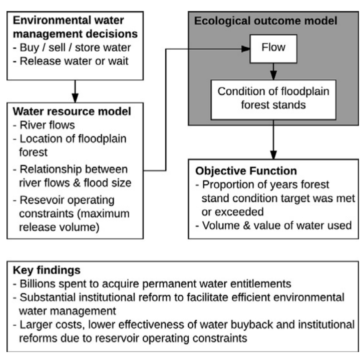
HIGHLIGHTS

- Regulation of river flows with reservoirs threatens many of the world's floodplain ecosystems.
- The decline of aquatic and floodplain ecosystems has motivated programs that return more water to the environment.
- In Australia's Murray-Darling Basin billions are being spent to return water to aquatic and floodplain ecosystems, managed by environment water holders.
- Recovery of floodplain forests by releasing water from reservoirs during periods of high flow is undermined by restrictions on river operations.
- Expensive water recovery programs can fail to achieve conservation aims without cooperation among stakeholders including reservoir operators.

GRAPHICAL ABSTRACT



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ABSTRACT

When freshwater resources become scarce there is a trade-off between human resource demands and environmental sustainability. The cost of conserving freshwater ecosystems can potentially be reduced by implementing institutional reforms that endow environmental water managers with a permanent water entitlement and the capacity to store, trade and release water. Australia's Murray Darling Basin Plan (MDBP) includes one of the world's most ambitious programs to recover water for the environment, supported by institutional reforms that allow environmental water managers to operate in water markets. One of the anticipated benefits of the Plan is to improve the health of flood-dependent forests, which are among the most endangered ecosystems globally because of river regulation and land clearance. However, periodic flooding to conserve floodplain ecosystems in the MDB creates losses to riparian landowners such as damage to fencing and temporary loss of access to flooded land. To reduce these losses reservoir operators restrict daily water release volumes. Using a model of optimal water management in Australia's southern MDB we estimate that current reservoir operating restrictions will substantially reduce the ecological benefits of investments made to recover water for the environment. The reduction in benefits is largest if floodplain forests decline rapidly without periodic inundation. In the latter

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Water entitlements
Water trading

circumstances, ecological losses cannot significantly be reduced by allowing environmental water managers to operate in water markets. Our findings demonstrate that the recovery of large volumes of water for environmental purposes and water market reforms are insufficient for conserving flood-dependent ecosystems without coordination and cooperation among multiple stakeholders responsible for water and land management.
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1. Introduction

The sustainable management of natural resources often involves a trade-off between human use and ecological health (Walker et al., 2009). Competition for scarce water resources will intensify as human populations grow and climates change (Vörösmarty et al., 2000). In response to increasing pressures on limited natural resources, attempts are being made to find an improved balance between consumptive human use and environmental needs (Arrow et al., 1995). In the case of water resources, this involves finding water use strategies that minimize the costs imposed when water is transferred from agricultural and domestic uses to the environment (Horne et al., 2017).

In a growing number of settings this transfer is facilitated by institutional reforms including the establishment of water rights frameworks in which the 'environment' is treated similarly to other rights holders (Bakker, 2014). The extent to which these reforms reduce the cost of transferring water to the environment depends on how the reforms affect environmental water managers' capacity to store, trade and release water (Connor et al., 2013; Grafton and Horne, 2014). This is shown, for example, when countercyclical water trading (selling to agricultural water users when water prices are high and buying when prices are low) allows water to be used for environmental purposes when its value for consumptive uses is relatively low (Loch et al., 2011). In addition to the introduction of water trading, further reductions in the cost of environmental watering can potentially be achieved by endowing the environmental water manager with an optimal portfolio of permanent water entitlements. Water entitlements are an ongoing claim to a share of the water resource. In many water markets, security-differentiated entitlements are available that differ according to their cost and the maximum allocation that can be made against water storages each year. Low security entitlements have a lower cost than high security entitlements but are less likely to receive water allocations when water availability is low (Lefebvre et al., 2012). Increasing the holdings of low-security entitlements as a source of environmental water allocations can potentially reduce costs without preventing ecological needs being met. However, in regions experiencing a drying climate, the reliability of water allocations to low security entitlements may decline to the extent that such entitlements cannot meet environmental needs.

One of the main potential impediments to cost-effective environmental water management is institutional fragmentation, in which uncoordinated actions are taken by different water stakeholders (Daniell et al., 2014; Daniell and Barrateau, 2014). This problem is particularly acute when there are conflicting aims of different stakeholders. In Australia's Murray-Darling Basin a source of conflict is the need for periodic flooding to conserve floodplain ecosystems, reflecting that floods create losses to riparian landowners such as damage to fencing and temporary loss of access to flooded land. These losses are often mitigated by reservoir operators through imposing restrictions on daily reservoir releases to reduce the likelihood of a flood event. In turn, these operating restrictions can potentially reduce the cost-effectiveness of environmental water recovery programs and institutional reforms to facilitate efficient environmental water management. In extreme circumstances, such restrictions can make it infeasible for an environmental water manager to create or prolong floods to conserve flood dependent ecosystems. This would make floodplain ecosystems wholly dependent on the frequency of natural flood events or necessitate costly investments in pumps and infrastructure to facilitate water delivery to those ecosystems (Pittock et al., 2013).

Substantial research has been undertaken on the potential benefits of institutional reforms to conserve freshwater dependent biota (see Hart, 2016a for a comprehensive review). Research has also been conducted on the potential for river operation restrictions to undermine institutional reforms (Hart, 2016a, 2016b). There is a need for quantitative estimates of the impact of such restrictions on the cost and feasibility of floodplain conservation. This information would usefully inform decisions on whether to relax those restrictions or invest in infrastructure that would allow water to be delivered to floodplain ecosystems without requiring large floods.

The primary aim of this study is to provide early empirical evidence on the extent to which river operation restrictions can reduce the benefits of water recovery programs and institutional reforms aimed at conserving floodplain biota. This requires a method for determining efficient water management strategies. If river operation restrictions substantially increase conservation costs or reduce conservation effectiveness despite water being managed efficiently, this would strengthen the case for a detailed assessment of options to mitigate such losses. Here, we define a water management strategy to be efficient if it minimizes the total volume of water required to achieve a specified ecosystem health target. We determine efficient water management rules using genetic programming (Potvin et al., 2004).

We apply the method to a case study focusing on a catchment within Australia's Murray-Darling Basin system, where one of the world's largest institutional reform programs to recover water for the environment has been implemented (Hart, 2016a, 2016c; Hart and Davidson, 2017). The water recovery program has been supported by the creation of an environmental water holder endowed with a portfolio of permanent water entitlements and the capacity to store and trade water. One of the primary anticipated ecological benefits of the Plan is the conservation of floodplain forests, which are among the most endangered ecosystems globally, threatened primarily by river regulation. Approximately half of the wetlands and floodplain habitats in the MDB could potentially be watered with releases from reservoirs in the absence of constraints on daily release volumes (Bunn et al., 2014; MDBA 2012). The ecological asset we consider is a floodplain forest of river red gum (*Eucalyptus camaldulensis* Dehnh) that requires periodic flooding to be maintained at a high level of health. The forest occupies discrete land parcels within the floodplain. In our analysis, parcels were defined by their distance from the edge of the river-bank. Distant parcels are inundated only with larger floods. An efficient water release strategy trades off immediate gains from small floods that inundate only part of the floodplain with potential future gains from waiting to inundate extensive areas. The likelihood of creating a larger flood later depends on future river flows, dam release capacity, and the extent to which environmental water holdings can be increased over time through storage and water trading.

2. Study area

We focused on 150 km of the lower Goulburn River Floodplain (Fig. 1), which lies between the Goulburn Weir (36.717 °S 145.170 °E) and its junction with the Murray River (36.103 °S 144.830 °E) in northern Victoria, Australia.

Detailed hydrological data and spatial data on river red gum stands were available for the study area. The hydrological data included a long-term dataset of simulated flows and dam-storage levels between

1891 and 2010 (Perera et al., 2005; DEPI, 2014). The same model provided estimates of water allocations to permanent water entitlement holders over this period. The relationship between river flows and spatial flood extent was estimated from a digitized floodplain map specifying the spatial extent of floods for different volumes (Water Technology, 2010). These were superimposed on a distribution map of river red gum stands on the floodplain (Cunningham et al., 2009) (Fig. 1) to determine the areas of floodplain forest inundated by floods of different extents (Table 1). These hydrological and spatial datasets allowed us to estimate the probability of achieving floods of specific extents with available water resources.

Water in the Goulburn River is released from two upstream storages; first from Lake Eildon to Goulburn Weir, from which it is released onto the floodplain. Creating augmented floods is constrained by an upper limit on daily water release volumes from these two upstream storages, which increases the risk that river levels may decline before the flood of desired size can be created. Current management guidelines stipulate a daily maximum release limit of 10 GL day^{-1} from Lake Eildon and this, along with tributary inflows, sets an upper limit on how much can be released from the Goulburn Weir. A lower limit may be imposed at Goulburn Weir to reflect concerns about adverse impacts on private land and water pumping infrastructure with releases of >4 GL day^{-1}. We considered a release limit of 10 GL day^{-1} to be current practice, and a larger hypothetical limit of 20 GL day^{-1} because it is technically feasible and large enough to substantially increase the frequency of opportunities to create augmented floods based on historic river flows (Perera et al., 2005). We estimated the effect of the larger release limit on the feasibility of maintaining river red gum condition at or above a specified target level. We also estimated the effect of the larger reservoir release limit on the minimum entitlement holdings required to achieve the forest health target and the associated total release volumes over the modelled time horizon.

2.1. Response functions for dieback and recovery of river red gum

Dieback of the river red gum on the Murray-Darling floodplain has occurred for decades (Mac Nally et al., 2011) and recovery programs have been established (MDBC, 2005). The temporal sequence of dieback and recovery has yet to be measured. By linking published work with our extensive fieldwork on these floodplains, we had sufficient understanding of the response of river red gum to water availability (rain, surface and ground water) to produce a set of plausible response curves, including estimates of upper and lower bounds on the capacity of red gum stands to persist in the absence of floods.

River red gums preferentially use surface water (precipitation and floods) if available, but rely on shallow groundwater during dry periods (Mensforth et al., 1994). Dieback of river red gum forests has occurred across extensive floodplain areas within the MDB due to reduced flooding frequencies under river regulation (Maheshwari et al., 1995), and the associated changes in groundwater depth and salinity (Cunningham et al., 2011). Forest dieback is mapped annually for the Murray River floodplain using remotely sensed data and validated with ground-based measurements (Cunningham et al., 2014). We used this stand-condition assessment as a measure of change in stands during periods of dieback and recovery (Table 2).

There are several dieback stages related to decreasing access to different water sources. With no regular flooding or substantial rainfall, trees deplete the surface soil moisture. River red gums shed leaves to reduce transpiration losses (Gibson et al., 1994), which allows trees to avoid water stress for several years between floods if they have access to groundwater. Long periods without flooding lead to the substantial reductions in crown extent (Cunningham et al., 2007). Groundwater is not a long-term solution because without replenishment from surface flows, water tables become lower and more saline (Jolly, 1996; Cunningham et al., 2011). Once access to groundwater is restricted by depth or salinity, trees experience severe water stress, rapidly shedding their remaining leaves. Such severe water shortages eventually lead to death (Franks et al., 1995).

River red gums respond rapidly to flooding or significant rainfall events with epicormic shoots on the trunk and branch tips (Bacon et al., 1993). This new growth senesces if soil moisture is subsequently depleted. If water availability is maintained through regular flooding, trees produce new shoots and increase crown extents (Souter et al., 2010).

Without flooding, trees maintain their crowns if soil moisture is adequate but decline in condition if using just groundwater; tree condition declines rapidly once groundwater is inaccessible. Given that we had no data on the temporal response of groundwater to rainfall and flood events, which may be more realistic, the condition of river red gum stands was modelled as a linear function of the number of years since the last flood. Condition was modelled in two scenarios representing lower and upper limits on the plausible range of intervals for complete dieback and recovery. Stand condition declined linearly from a maximum value of 10 (full crown) to 0 (dead trees) over 10 years ('moderate linear' scenario) or 20 years ('extended linear' scenario). On reaching 0, the trees are dead and do not recover regardless of flooding. At condition level 10, no further improvement in condition can occur and further flooding maintains condition at this level.

2.2. Water trading

The Commonwealth Minister responsible for Water can stipulate operating rules governing water trading by the Commonwealth Environmental Water Holder (CEWH) [sect. 109 of the Water Act 2007 (Commonwealth of Australia, 2017)]. Environmental water in the Goulburn system is held by the CEWH and two other entities, the Victorian Environmental Water Holder (VEWH) and the MDBA, with the CEWH being the largest holder. Water acquisitions by the CEWH must be financed by sales of water holdings by the CEWH. The CEWH cannot borrow against potential future sales and the CEWH generally is not given more water from other sources. We considered trading of allocations but not trading of entitlements and we assumed that allocation purchases can be made only with the proceeds of previous water-allocation sales.

Data obtained from the Victorian Government on average market prices and historic water allocations for high and low reliability water shares between 2003 and 2012 (Table 3) were used to estimate the following relationship between average market price P (\$/ML) and water allocations:

$$P = \exp(-0.011\{HRWS + LRWS\} - 614.0) - 229.6),$$

where $HRWS$ is the allocation (% of entitlement volume), announced at the closing of the water year (June 30) of high reliability water shares and $LRWS$ is the allocation of low reliability water shares (% of entitlement volume). The relationship reflects that prices were highest in dry years with relatively low water allocations, and typically declined with increasing water availability. However, this relationship should be viewed with caution because it is based on a very small dataset involving only 9 observations. One of these observations (2008) was excluded based on expert opinion that the average price reached in that year not representative of longer term market behaviour. This reflects the occurrence in 2008 of major institutional reforms to water storage and trading rights (Victorian Water Register, undated). Prices in 2008 (\$562/ML) substantially exceeded prices in all other years with comparable water availability (57% allocation).

3. Modelling methods

3.1. Overview

We applied genetic programming (Potvin et al., 2004) to determine an efficient environmental water management strategy. A strategy

consists of a set of rules that determine when to buy/sell, release and store ("carry over") water in different circumstances that might arise over the future (different potential "states" of the system). The system state is defined in terms of four attributes: river flows, reservoir storage levels, funding for acquiring water and river redgum condition in different zones within the floodplain.

There are computational challenges in determining an optimal decision rule for each possible state of the system because of the large number of possible state-decision rule combinations to consider. Genetic programming allows for near-optimal decision rules to be developed by determining an initial set of candidate rules, simulating their outcomes and assessing outcomes in terms of performance metrics ("fitness"). Rules that perform best are selected, other rules are eliminated, and new candidate rules are generated that may outperform existing rules. The processes that are simulated to evaluate performance include monthly river flows, annual allocations of water to the environmental water holder (EWH), purchase and sale of water by the EWH, and release of water by the EWH to inundate part or all of the floodplain. The criteria for evaluating performance are the average forest condition score and the proportion of years in which this score equally or exceeded a specific target score. The form of cost considered was the total quantity of water used over the time period.

The decision rules are of a particular form. Each rule is a decision tree, analogous to (if-then-else) logical expressions that specify which action/s to take (for example, whether to buy water and create a small flood) based on the values of the state variables. The collection of decision trees at any time is the 'population' considered in the genetic algorithm. This population is evaluated according to its success in

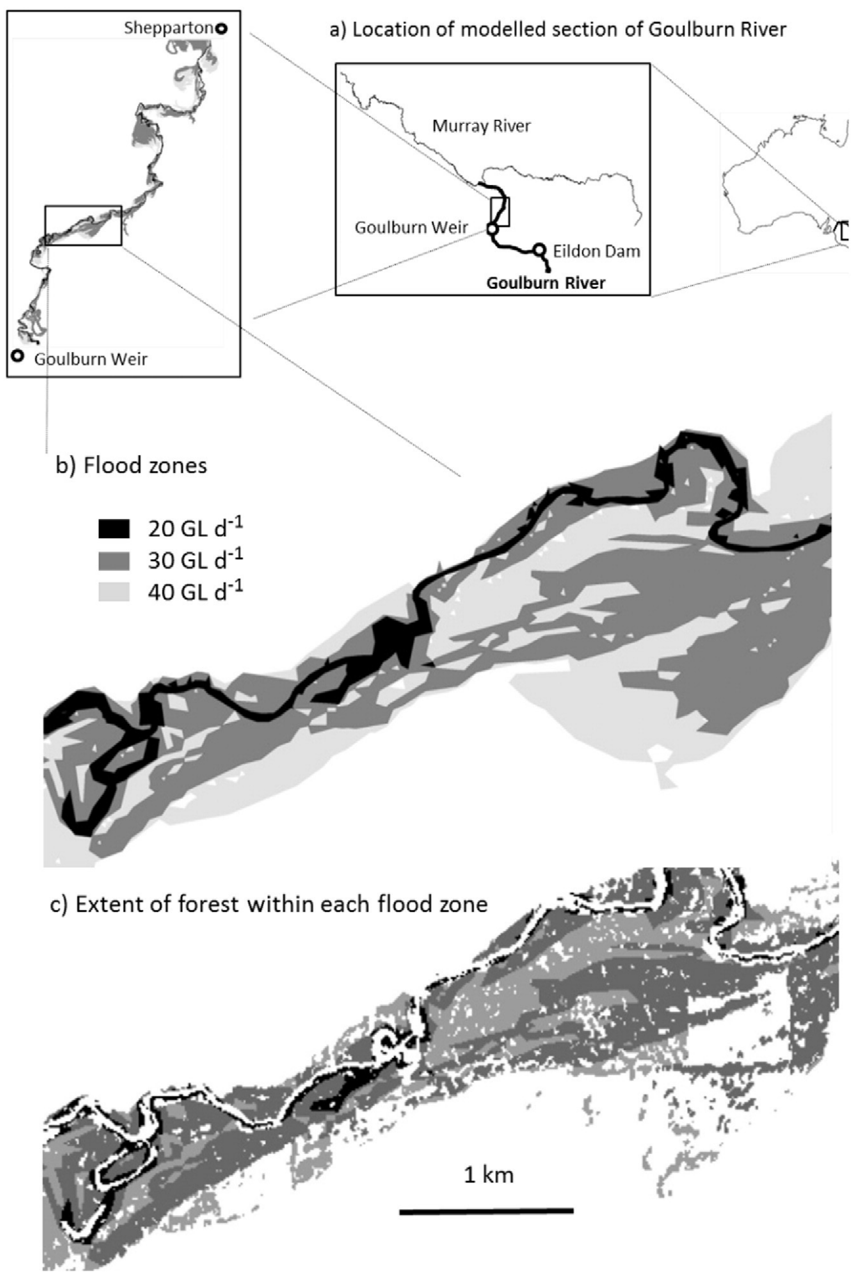

Fig. 1. Maps of the study floodplain showing: (a) the location of the modelled section of the Goulburn River in south-eastern Australia, the main infrastructure and the adjacent Murray River. An example section of the study floodplain showing (b) the extent of the different flood zones and (c) the extent of forest within these flood zones, determined as the intersection of the flood zones with remaining forest.
Source: CSIRO flood mapping (G. Earl, Goulburn Broken Catchment Management Authority, unpublished data) and red gum extent map (Cunningham et al., 2009).

Table 1
Tree area per floodplain zone in the Lower Goulburn River Floodplain.

Flood size ($GL\ day^{-1}$ for 7 day)	Flood area (ha)	Forest area inundated (ha)
20	822	172
30	1241	214
40	1761	260

maintaining forest stands at an acceptable level of health using as little water as possible. Increased forest condition scores in any given year indicates a more effective strategy and increased water use indicates a less effective strategy. These effectiveness criteria are summed for an aggregate measure of effectiveness for a given strategy. This is stage one of the calculation of 'fitness' used in determining decision rules (Eq. (2)).

Two sub-problems were considered, a yearly problem and a monthly problem, because some state attributes change yearly (e.g., river red gum condition) and other attributes (river flow) change monthly. Two examples of solutions to the monthly problem illustrate the approach:

Solution 1:
    If natural flood this year = 1
        Create flood level 2
        Maintain storage level at 35.578
    Else
        Maintain storage level at 50.1229
        Create flood level 3

Solution 2:
    If natural flood this year = 2
        Maintain storage level at 25.0978
    Else
        Create flood level 2
        Maintain storage level at 141.42

The order in which the actions appear determines which of the targets is met in circumstances where only one of the targets can be met, with the target higher on the list being given first priority.

The solution to the yearly problem determines which of the monthly solutions to implement, as illustrated by the following example of a solution that applies the two monthly strategies presented above:

If price < 51.3516
    If condition of second flood zone = 6
    Implement monthly strategy 1
Else
    Implement monthly strategy 2
Else
    Implement monthly strategy 1

The solution to the yearly problem can be thought of as classifying the years into groups which can each be dealt with using an appropriate monthly strategy. The monthly strategy classifies the months into groups which can be dealt with using an appropriate monthly action. Modelling decision strategies in this way has the advantage of not requiring categories of state variables (for example "wet years" and "dry years") to be pre-determined in an arbitrary way. The state categories are determined as part of algorithm process in a way that is most relevant for decision making.

Table 2
Stand condition classes, their associated stand condition scores and the crown extent of trees in an average stand within a condition class. Crown extent is the proportion of the existing branching structure that contains foliage (Cunningham et al., 2007).

Stand condition class	Stand condition score	Average crown extent
Good	8.1–10.0	80–100%
Declined	6.1–8.0	60–80%
Poor	4.1–6.0	40–60%
Degraded	2.1–4.0	20–40%
Severe	0.0–2.0	0–20%

3.2. The system

The reservoir, river and surrounding flood zones are modelled as a state space involving the following variables, which can be altered by the actions the decision maker performs:

$H_{1,y}$ – The health state of redgum stands on the first flood zone.
$H_{2,y}$ – The health state of redgum stands on the second flood zone.
$H_{3,y}$ – The health state of redgum stands on the third flood zone.
S_y – The quantity of water in storage.
F_y – The current amount of funding available for purchasing water.

Floods are created by natural occurrence of high river flow or with supplementary water releases from storage in the reservoir. The flood categories considered were based on the available information on inundation extent (Water Technology, 2010): (1) 0–140 GL $month^{-1}$, (no flooding); (2) 140–210 GL $month^{-1}$ (zone 1 flooded); (3) 210–280 GL $month^{-1}$ (zones 1 and 2 flooded); and (4) > 280 GL $month^{-1}$ (zones 1, 2 and 3 flooded). For the purposes of the analysis, a maximum storage limit of 180 GL for environmental water holdings was considered; this volume is just larger than the total volume required to flood Zone 1 and is approximately 50% larger than the environmental water holder's entitlement holdings at the time this analysis was conducted.

Forest stand condition is modelled as a linear function of the number of years since the last flood, decaying by one step each year there is no flood and increasing by one step in each year there is a flood. A forest stand that declines to a condition score of zero is considered unable to recover regardless of further flooding. At the maximum condition level (values of 10 and 20 in the rapid dieback, and slow dieback, scenarios, respectively) no further increase in condition can occur and any flooding that occurs would maintains the condition at this level.

The following values are taken from the data rather than being generated by decisions:

Py – The price of water in year y.
$A_{l,y}$ – The low security allocation percentage in year y.
$A_{h,y}$ – The high security allocation percentage in year y.
$L_{y,m}$ – The river level (flow) in GL/month in year y and month m.

3.3. Criteria for evaluating effectiveness

The effectiveness of a solution was evaluated by the mean forest stand condition score and by the proportion of years in which a stipulated target condition score was met or exceeded. We set the stand condition target at 70% of the maximum feasible score because scores rarely reached 75% in simulations but often exceeded 70%, making this an achievable score within the upper range of feasible scores. Although 70% is substantially less than the maximum condition, it would ensure the long-term maintenance of river red gum on the floodplains. The primary measure of cost considered was the total quantity of water used over the time period. In our results we also report the value of water obtained over the time period offset against the value sold back to the market. Allocations were considered to be obtained at the price of water in the year in which they were allocated.

3.4. Yearly problem

The yearly problem considers the following variables, indexed by the year (y):

Table 3
Historical water prices and allocations.[a]

Year	Volume weighted average price ($/ML)	Max alloc (%) at end of the year
2002–03	364	57
2003–04	67	100
2004–05	60	100
2005–06	57	100
2006–07	441	29
2007–08	562	57
2008–09	339	33
2009–10	149	71
2010–11	26	100
2011–12	17	100

[a] Source: Barry James. Water Resources Division, Office of Water, Department of Sustainability and Environment. Prices

$H_{1,y}$: Condition of river red gum stands in the first flood zone (lower elevation).
$H_{2,y}$: Condition of river red gum stands in the second flood zone (middle elevation).
$H_{3,y}$: Condition of river red gum stands in the third flood zone (high elevation).
T_y: Flow in the previous year (GL).
S_y: Volume of stored water (GL).
F_y: Current funding available for purchasing water ($).

All variables are positive (or zero) real numbers except for the forest condition states ($H_{1,y}$, $H_{2,y}$, $H_{3,y}$), which are integers between 0 and 10 inclusive.

Each candidate rule involves a test that determines what action to take based on whether the values of the state variables are less than, equal to, or greater than specified values. The form of test applied in the yearly problem depends on the state variable that the test operates on. The health state variables ($H_{1,y}$, $H_{2,y}$, $H_{3,y}$) are integer variables and the tests $<$, $=$ and $>$ are provided with their usual definitions. For the real variables (all state variables other than forest condition) only the $<$ test is applied instead of $<$, $=$ and $>$ tests. This reflects that equality of two real values is so unlikely that an equality test would almost certainly fail and therefore would not be useful as a classification tool. By a similar argument the $>$ test would almost certainly succeed where a $<$ test would fail and would fail where a $<$ test will succeed. Thus the $>$ test adds nothing to the classification process.

An initial population of solutions is generated at random, assigned fitness scores and then updated iteratively through a series of replacements (a population of 200 was used for the yearly problem solutions). Tournament selection (Miller and Goldberg, 1995) is used wherever selection of a weak or strong member of the population is needed, selecting some number of individuals at random and choosing the fittest or weakest among them. This ensures that weak individuals can still get an opportunity to reproduce and pass on their genetic material but do so far less frequently. At each iteration, a weak individual is selected and replaced by a new individual created either entirely at random or by one of the two reproduction methods described below (mutation and crossover). A fitness score is calculated for the new individual based on the outcomes of their behaviour (see below). The next replacement iteration includes this individual as a potential source of genetic material for the mutation or crossover methods of reproduction.

Fitness for the yearly problem solutions was calculated in two stages. Firstly, the solution is executed on the data set described above. At the end of each year, the health states of each zone, along with the amount of water allocated to the decision maker and the quantity bought or sold is used to create a fitness score calculated according to the following formula:

$$s_y = \nu_1 H_{1,y} + \nu_2 H_{2,y} + \nu_3 H_{3,y} - c\left(a_y + p_y\right) \tag{1}$$

where s is the score indexed by year, ν_n is the weighting of each of the flood zones, c is a scale factor to control for how valuable water is considered to be, and a and p are the amounts of water allocated and purchased in that year, respectively. The inclusion of the allocation and purchase quantities encourages minimization of water usage while the scale factor c controls the priority between maintaining stand-condition and water usage.

The second stage of the solution applies the following formula:

$$S = \left(\frac{\gamma}{\gamma + R}\right)\left(\frac{\beta}{\beta + c}\right)\left(\frac{\alpha}{\alpha + u}\right)\sum_y S_Y \tag{2}$$

The sum of yearly fitness scores, $\sum_y S_Y$ is multiplied by three scale factors. The first scales by a value depending on the size of the decision tree which is the number of tests and actions in the tree. The parameter α controls how significant this effect is. In this way we can encourage smaller trees rather than large ones which likely either contain large redundancies or would overfit the problem. Overfitting occurs when the solutions to the problem contain information specific to the particular sample of the stochastic process used for learning. As such, overfitted solutions do not generalise well to subsequent samples as they do not operate on characteristics specific to the overall process. Consider the example of a decision tree with the same number of leaves as there are input data points. In this case the solution could classify each data point into a different category and have the most appropriate action for each, thus it would perform optimally on the training dataset. However, if a new dataset were used, the categories would not necessarily be optimal because the decision tree does not extract any general properties of the system. The parameter c is the number of other trees of the same size, and β controls its effect. The final scale factor is related to the total quantity of water released (R). The parameter γ controls its effect.

3.5. Monthly problem

The variables considered in the monthly problem are:

m – The month index $(0-11)$.
$L_{y,m}$: flow rate in year y and month m (ranges 0:11).
$f_{y,m}$: highest flood (natural or otherwise) in year y occurring by month m.

Monthly problem solutions are given access to the month index in order to allow seasonal variation to be predicted, for example, many solutions identified September as an important year for releasing water, striking a balance between waiting for a natural flood and releasing to create artificial ones. The month and flood variables are both integer variables and thus have the $<$, $>$, $=$ tests available. The flow rate is a real variable and thus only has the $<$ test available.

The actions available to solutions to the monthly problem are described by either one variable or three variables, depending on whether water trading is enabled. The variables are:

Tf – The flood target of the action.
Ts – The storage target of the action.
Priority – A Boolean value that resolves potential conflicts between the two targets.

The actions depend on whether water trading is allowed. With trading enabled, only the flood target is used. The priority variable resolves conflicts that may arise between the flood and storage targets. This can

be illustrated by considering the hypothetical case where achieving the flood target requires 50 GL of water to be released and the storage target is 30 GL below the current storage level. If funding is insufficient to purchase enough water to allow both the flood and storage targets to be met simultaneously, the priority variable determines which of those targets will be met. If priority is given to immediate creation of a flood the 50 GL required to achieve this will be released and water purchased to increase storage as close as possible to the storage target. If priority is given to storage no water would be released and water would be purchased to increase storage as close as possible to the target level without exceeding the target.

Fitness for the monthly problem solutions is determined by two factors, the number of yearly solutions that use the particular monthly solution (d) and the size of the solution tree (u). This is specified by Eq. (3):

$$S = \frac{dx}{x+u} \tag{3}$$

where *x* is a scaling parameter. The reason for adjusting the aggregate measure of effectiveness by a factor relating to the size of the decision tree for that solution is to introduce pressure for simpler solutions (i.e., smaller decision trees). Inclusion of the parameter *d* ensures that solutions to the monthly problem that are successful will be used more frequently than solutions which are not successful.

3.6. Reproduction

'Reproduction' of the decision trees that make up the yearly and monthly solutions is accomplished by applying the standard two forms of genetic programming operators, mutation and crossover. Mutation is the replication of a parent solution with random errors assigned. There is a fixed probability that each node in the decision tree may be altered. A node may be replaced only with another node of the same type (i.e. action or test), although the actions may change priority and the tests may change the variable tested. For mutation of yearly solution actions, a randomly selected monthly solution is selected or a new one generated to replace the one copied. Mutation of yearly solutions drives the evolution of the monthly solutions. 'Crossover' is the selection of two parents and is akin to sexual reproduction in biological organisms. One parent contributes the base of the decision tree, the other a branch. If the point of crossover in either tree is a leaf node, a retry is triggered, so there is ca 0.25 probability that the crossover will consist of a leaf, and a 0.75 probability that it will be a larger structure. Both the yearly and monthly solutions 'evolve' to generate new solutions.

3.7. Algorithm progression

An initial population of yearly and monthly solutions, tests and actions were generated randomly. The yearly solution population was fixed. The populations of the monthly solutions, tests and actions, vary in size but are culled if too large to introduce competition. Tests and actions are culled at random if not currently used in any solutions, but the monthly solutions are omitted by tournament selection on fitness scores. Whenever a new monthly solution, test or action is required during the process of mutation or the generation of a new entirely random decision tree, it is randomly selected from the existing population or generated and added to the population. New monthly solutions are generated through a mutation of an existing solution, crossover of two existing solutions or from a completely random new solution. Every step involves the replacement of one low performing yearly solution with a new solution generated from existing ones or at random. After 100,000 replacements the best solution is returned.

The genetic programming approach is summarised in Fig. 2.

4. Results

With the exception of the most recent Millennium Drought between 1997 and 2010 under river regulation, unaugmented floods probably occurred frequently enough to maintain river red gum stands in flood zone 1. However, more distant stands (flood zones 2 and 3) could be maintained with high probability only by using Environmental Water Allocations (EWAs) to augment floods.

4.1. Minimum entitlement volumes for conserving the more distant tree stands

The decision to create large or intermediate augmented floods is sensitive to the entitlement volume held by the EWH, the form of entitlements held (high security, low security or both) and whether trading is allowed. The maximum reservoir release rate was set at the current level of 10 GL day^{-1}.

If there is a high-security entitlement holding of between 5 and 10 GL and water trading is allowed the best management strategy is to create only large augmented floods, with water stored when only zone 2 floods can be created (Table 4). If only low-security entitlements are held, a much larger entitlement of 20–30 GL is required and water trading must be allowed. The capacity to trade water was critical for this strategy because of larger variability in allocations with this form of entitlement, with low or no allocations made during droughts. If water trading is not permitted, creation of large floods is the best strategy only if the high-security entitlement volume is increased from 5 to 10 GL to 10–20 GL. It is infeasible to maintain all red gum stands in good condition (score ≥ 7) if only low-security entitlements are held and if water trading is not allowed.

4.2. Meeting environmental targets at least cost under alternative ecological response scenarios and dam release limits

It was not possible to ensure that the stand condition target would be achieved in any of scenarios considered because water availability is stochastic so we specified a required minimum probability of achieving the target. To assess the implications for environmental water management decisions of requiring a high probability of achieving the forest condition target, we set this probability at 0.75. The required level of confidence of achieving conservation targets will, in practice, be set by the management agency.

One of the main results is that the current reservoir release limit of 10 GL day^{-1} is insufficient to maintain trees in the third flood zone at condition level ≥ 7 with the required confidence if trees decline rapidly without flooding. Our reporting of results in the rapid dieback scenario (Table 4) therefore focuses on the hypothetical larger reservoir release limit of 20 GL day^{-1} ('high release limit'). Allowing water trading in this scenario reduced the total volume of water required and the cost of water substantially for the entitlement portfolios considered. Without trading, the ecological condition target could not be met for the low security portfolio because of the lower water allocations received in many years with this portfolio.

The form of monetary value reported in Tables 4 and 5 depends on whether the environmental water holder can buy and sell water on the allocation market. If trading is allowed this monetary value is the total revenue from water purchases less expenditure on water acquisitions by the water holder. If trading is not allowed the reported monetary value is the dollar value of water used based on price at the time it is released. It can be noted that the value of water used is larger for the no trade scenario when dieback is rapid or if there is a large daily release limit when dieback is slower and the entitlement portfolio includes low security entitlements. This reflects that in these scenarios, the absence of trade occasionally forces the environmental water holder to release water when it is relatively expensive. When trading is permitted, the environmental water holder can sell the water to other users

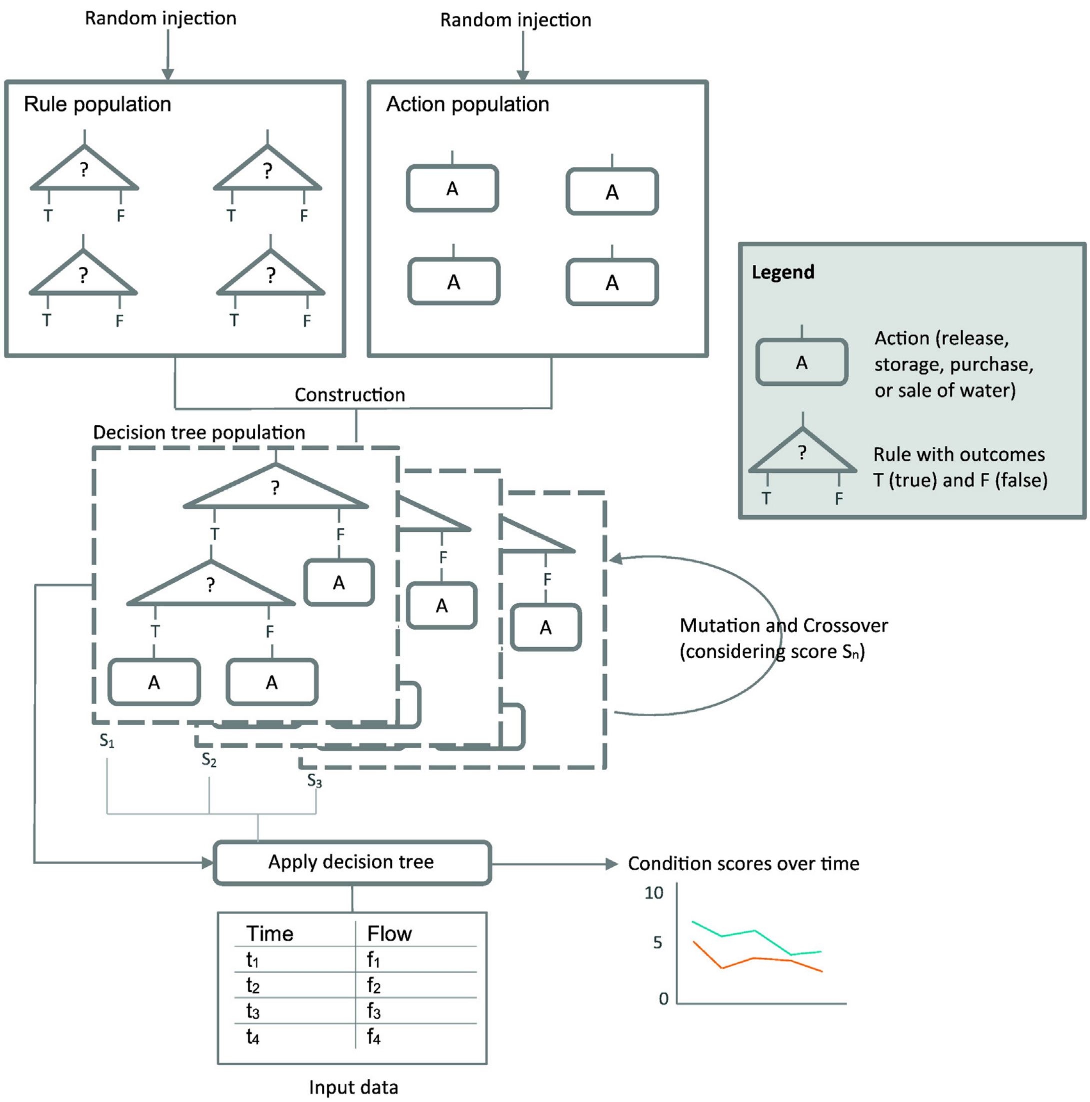

Fig. 2. Overview of genetic programming algorithm. Random injection is the process of introducing new rules and actions into the population to maintain variation among the population. Decision trees are constructed out of the current population of rules and actions. Applying the decision trees to the dataset produces a score *Sn* which influences the chance that a tree will be selected for reproduction.

when its price is high and use the revenue obtained to acquire and use water when its cost is lower.

Table 5 illustrates that the stand-condition target in the third flood zone can be achieved at lower cost (less water, lower entitlement volumes and lower value of water used) if the daily reservoir release limit is increased from its current level of 10 GL to 20 GL. Costs are lower in this scenario because of increased opportunities to achieve the required flood frequency, assisted by water trading and/or storage. The required entitlement holdings and the value of water used fall to less than half their levels when the 10 GL limit is maintained.

Holding low-security entitlements only or a mixed portfolio is more cost-effective than holding only high-security entitlements for the scenarios considered. With the larger daily water release limit, both the high-security and mixed portfolios had a minimum required entitlement volume of 10 GL years^{-1} but the mixed portfolio included 5 GL of low-security entitlements, which has a cost approximately one tenth that of the high-security entitlements (National Water Commission, 2012). However this result should be viewed with caution because allocations made to low security entitlements are much lower over recent years than the estimates of allocation frequency made in the REALM model results used in this analysis (Table 6).

Table 4
Minimum entitlement volumes for maintaining river red gum stands in the most distant flood zone in the scenario where trees decline rapidly in the absence of floods (i.e. 10 years for total decline).

	No trading allowed (GL)	Trading allowed (GL)
High security	10–20	5–10
Mixed security	20–30	10–20
Low security	Never	20–30

Table 5
Costs of maintaining the stand condition target (score ≥ 7) in the highest part of the floodplain (zone 3) with high probability ($P = 0.75$) under alternative scenarios on water trading for the high reservoir-release capacity (20 GL/day) when tree dieback is rapid (10 years). Results are presented as sets of three values (GL, GL, A$): the entitlement holding, the total amount of water used over the 110-year simulation, and a monetary value of the water used.

	High (GL, GL, A$)	Mixed (GL, GL, A$)	Low (GL, GL, A$)
Trade	20, 2342, 51,261	30, 3153, 54,646	60, 3384, 46,084
No trade	60, 2597, 62,139	60, 3186, 73,116	–

Table 6
Costs of maintaining the stand condition target (score ≥ 7) in the highest part of the floodplain (zone 3) with a high probability ($P = 0.75$) under alternative scenarios on water trading and reservoir-release capacity when tree dieback is slow (20 years). Results are presented as sets of three values (GL, GL, A$): the entitlement holding, the total amount of water used over the 110-year simulation, and the dollar value of water used.

		High	Mixed	Low
Low release limit	Trade	20, 2379, 58,960	30, 2232, 61,257	40, 2320, 31,031
	No trade	40, 1942, 59,003	40, 2509, 57,989	120, 2396, 30,945
High release limit	Trade	10, 2254, 25,216	10, 1965, 20,107	20, 2096, 14,017
	No trade	30, 1784, 51,701	40, 2114, 51,726	50, 2378, 29,046

5. Discussion

Reservoir release capacity and water trading restrictions have significant but different effects on the cost and feasibility of meeting stand-condition targets. Release restrictions reduce opportunities for creating floods whereas trade restrictions reduce opportunities for shifting water availability over time. There are potentially significant advantages in shifting and expanding water availability through countercyclical trading but these gains are realized only if flooding opportunities arise frequently enough. This did not occur in our analyses if current reservoir release limits are maintained or if trees decline rapidly without flooding. This explains our finding that the largest gains from allowing water trading occurred when stand condition declined relatively slowly (over 20 years) and with an increased reservoir release limit. This finding adds support to previous findings that allowing environmental water holders to engage in water trading is likely to provide benefits in excess of the costs involved (Connor et al., 2013).

The current limit on reservoir releases has the largest influence on the cost and feasibility of conserving distant river red gum stands. If tree dieback is rapid, maintaining the reservoir release limit is likely to prevent distant stands of red gum from being maintained in good condition, regardless of whether trading is allowed. This reflects that when dieback is rapid, insufficient opportunities are likely to arise for creating or expanding floods to achieve the required forest condition target when a maximum volume of only 10 GL/day can be released. No augmented floods have been created in the study region since the establishment of the Commonwealth and Victorian Environmental Water Holders (the CEWH, and VEWH, respectively). Current reservoir operating practice requires that 4 weeks' notice be given of any intention to release water volumes larger than 3 GL/day. The difficult in accurately predicting river flows 4 weeks in advance implies that these operating requirements will make it even more challenging to create or prolong augmented floods in the study region, particularly for higher parts of the floodplain.

The current reservoir release limit also increases costs in scenarios where it is feasible to achieve floodplain forest conservation targets. Entitlement holdings and the value of water used for conservation purposes fall substantially when the release limit is doubled. This demonstrates the significant influence of reservoir operating restrictions on the cost-effectiveness of investments in water recovery for the environment in our case study.

Modifying the portfolio of entitlements held by the environmental water holder could potentially reduce the cost of conserving floodplain ecosystems but this depends on the future reliability of allocations to low security entitlements. In our case study, the EWH holds a mix of high- and low-security water entitlements, with <10% being low-security entitlements at the time of this analysis (Australian Government, 2015). The allocation of water against the latter entitlements has been very low in recent years, with only 5% allocated in 2017 and no allocations since the late 1990s. This is a much lower frequency of allocations than was estimated in the REALM model simulations on which this analysis is based. If allocations remain low in the future this would reduce the scope to achieve cost reductions by adjusting the environmental water holder's entitlement portfolio, despite the much lower cost of low security entitlements.

6. Conclusions

Floodplain forests are among the most endangered forests globally (González et al., 2016) and are threatened within the study region (Hart, 2016a, 2016b; Mac Nally et al., 2011). Our analysis demonstrates that recovering substantial volumes of water for the environment and implementing broad institutional reforms to facilitate more effective environmental water management may not be enough to conserve floodplain forests. In Australia's MDB, investments made to recover water for the environment were made before agreement was reached with reservoir operators about arrangements for creating and prolonging flood events to conserve floodplain ecosystems. Although much of the recovered water was obtained from willing sellers in markets, cooperation also will be required from other stakeholders that may be affected by the use of environmental water holdings, including riparian land users and reservoir operators. Without this cooperation the required changes in river operations to allow floods to be created or expanded when needed may not occur, reducing the benefits of one of the world's most ambitious plans for recovering water for the environment.

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